US006219172B1

(12) United States Patent
Yariv

(10) Patent No.: US 6,219,172 B1
(45) Date of Patent: Apr. 17, 2001

(54) SAMPLING AND PROCESSING SIGNALS BY USING OPTICAL PULSES

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/193,551**

(22) Filed: **Nov. 17, 1998**

Related U.S. Application Data

(60) Provisional application No. 60/065,249, filed on Nov. 18, 1997.

(51) **Int. Cl.**[7] **G02F 1/03**; H04B 10/04

(52) **U.S. Cl.** **359/264**; 359/188; 359/181

(58) **Field of Search** 359/264, 181, 359/188, 184, 245

(56) **References Cited**

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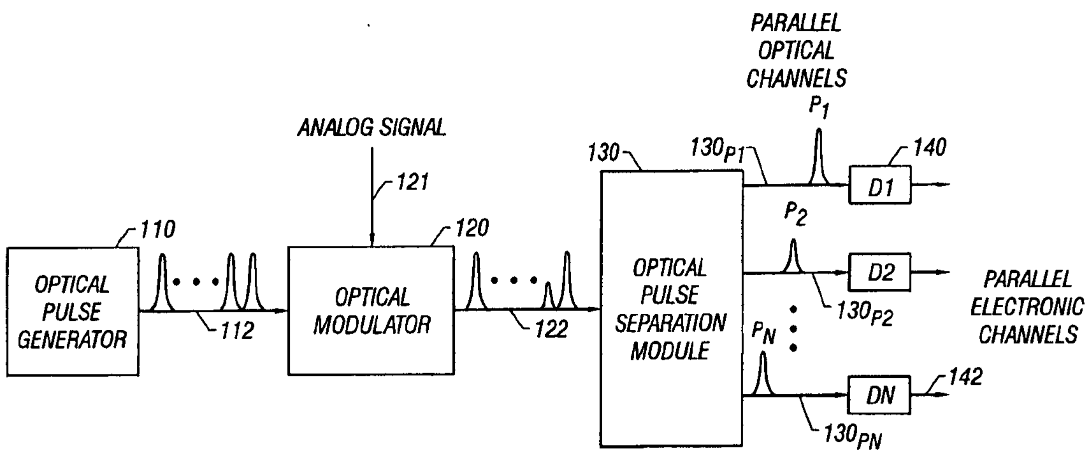
(57) **ABSTRACT**

A device and technique to sample an analog signal by optical pulses at a high sampling rate. Parallel analog-to-digital conversion channels can be implemented to achieve high-speed analog-to-digital conversion.

31 Claims, 10 Drawing Sheets



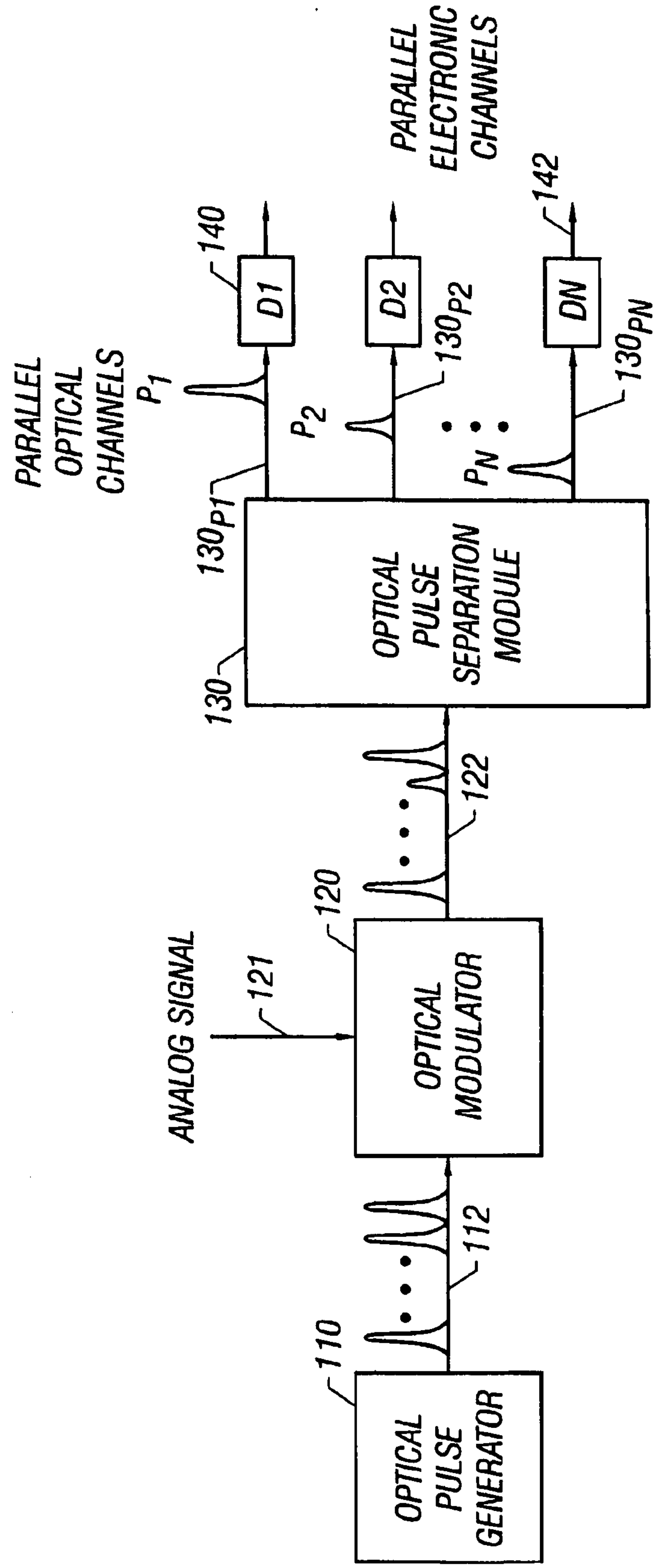

OPTICAL PULSE GENERATOR
110
112
ANALOG SIGNAL
121
OPTICAL MODULATOR
120
122
OPTICAL PULSE SEPARATION MODULE
130
130P1
PARALLEL OPTICAL CHANNELS
P1
P2
PN
130P2
130PN
D1
D2
DN
140
142
PARALLEL ELECTRONIC CHANNELS

FIG. 1

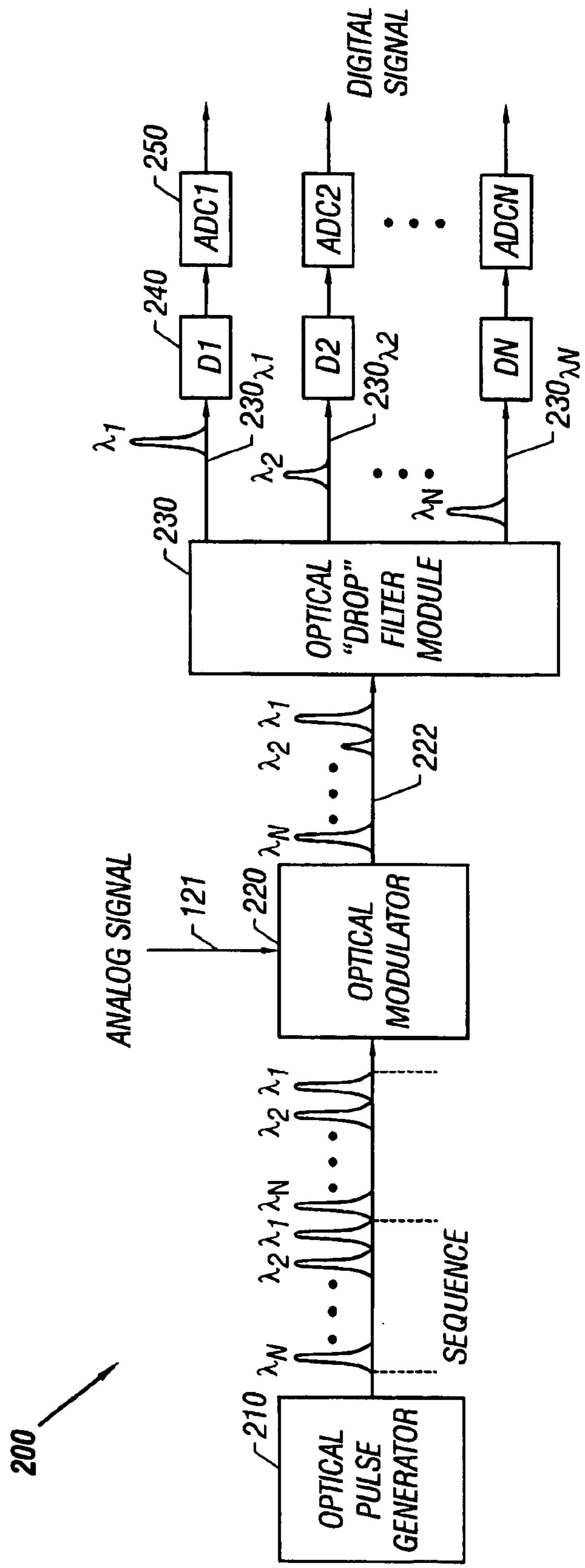

200
OPTICAL PULSE GENERATOR
210
SEQUENCE
ANALOG SIGNAL
121
220
OPTICAL MODULATOR
222
OPTICAL "DROP" FILTER MODULE
230
$230_{\lambda 1}$
$230_{\lambda 2}$
$230_{\lambda N}$
D1
D2
DN
240
ADC1
ADC2
ADCN
250
DIGITAL SIGNAL

FIG. 2

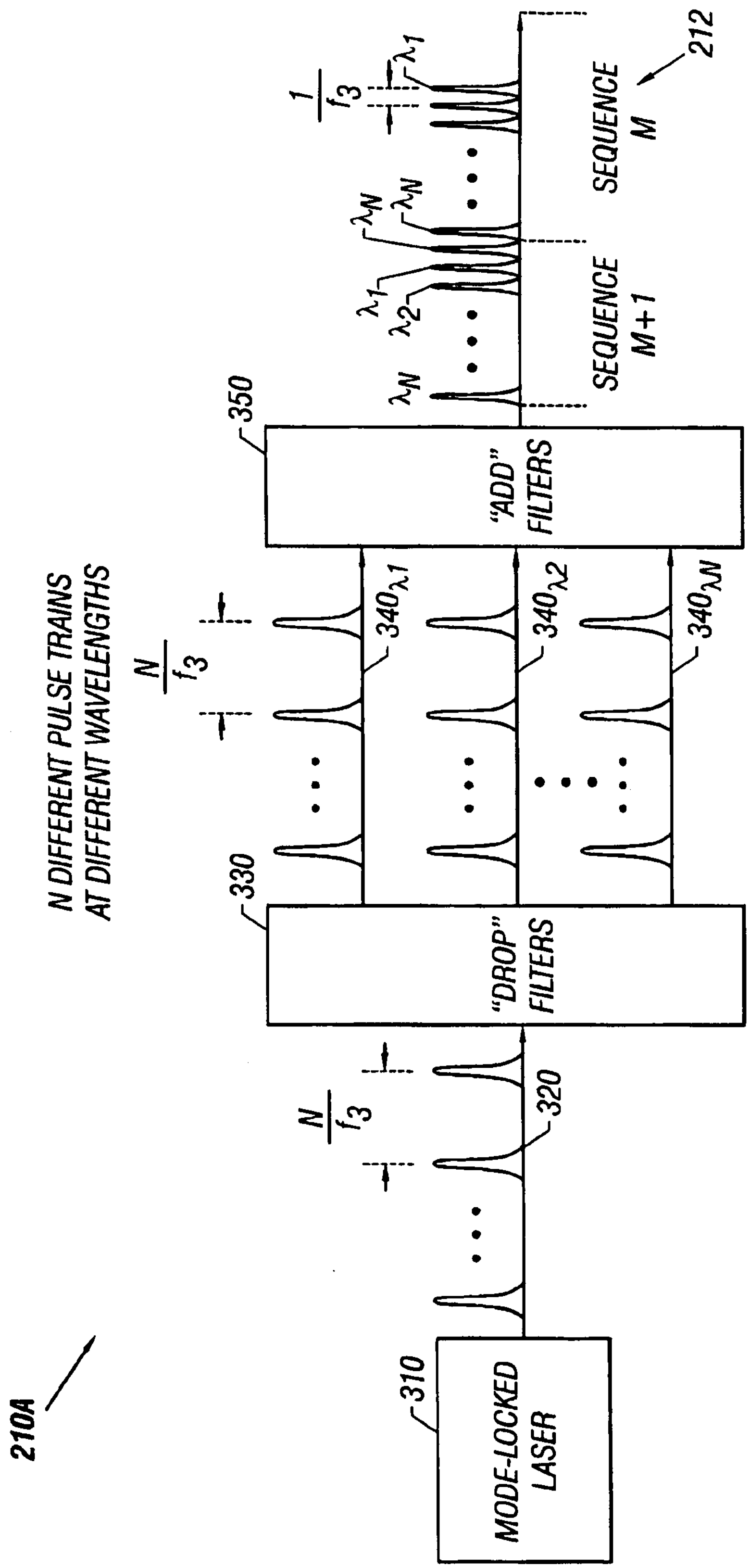

210A
MODE-LOCKED LASER
310
320
"DROP" FILTERS
330
N DIFFERENT PULSE TRAINS AT DIFFERENT WAVELENGTHS
$\frac{N}{f_3}$
$340_{\lambda 1}$
$340_{\lambda 2}$
$340_{\lambda N}$
"ADD" FILTERS
350
λ_N
λ_2
λ_1
λ_N
λ_N
λ_1
$\frac{1}{f_3}$
SEQUENCE M+1
SEQUENCE M
212

FIG. 3A

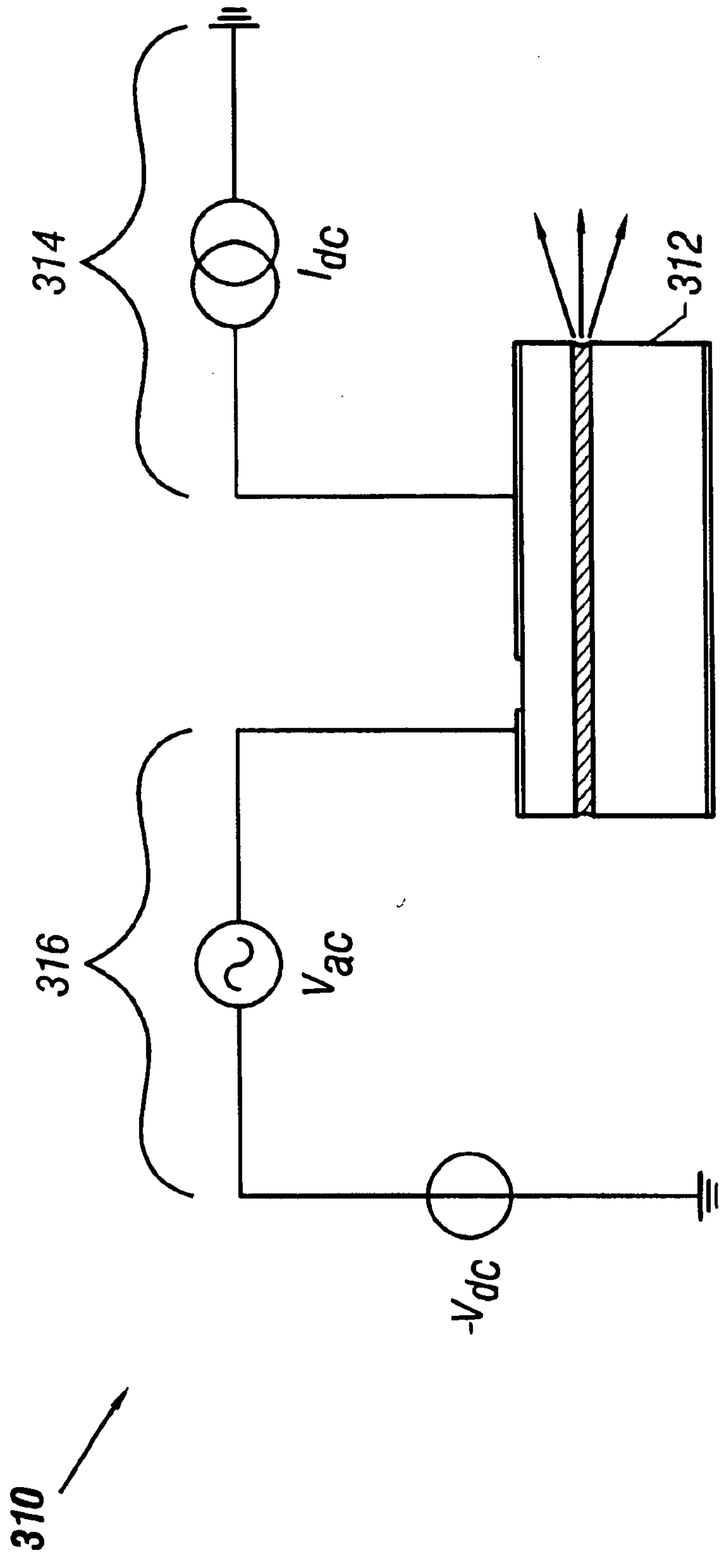


FIG. 3B

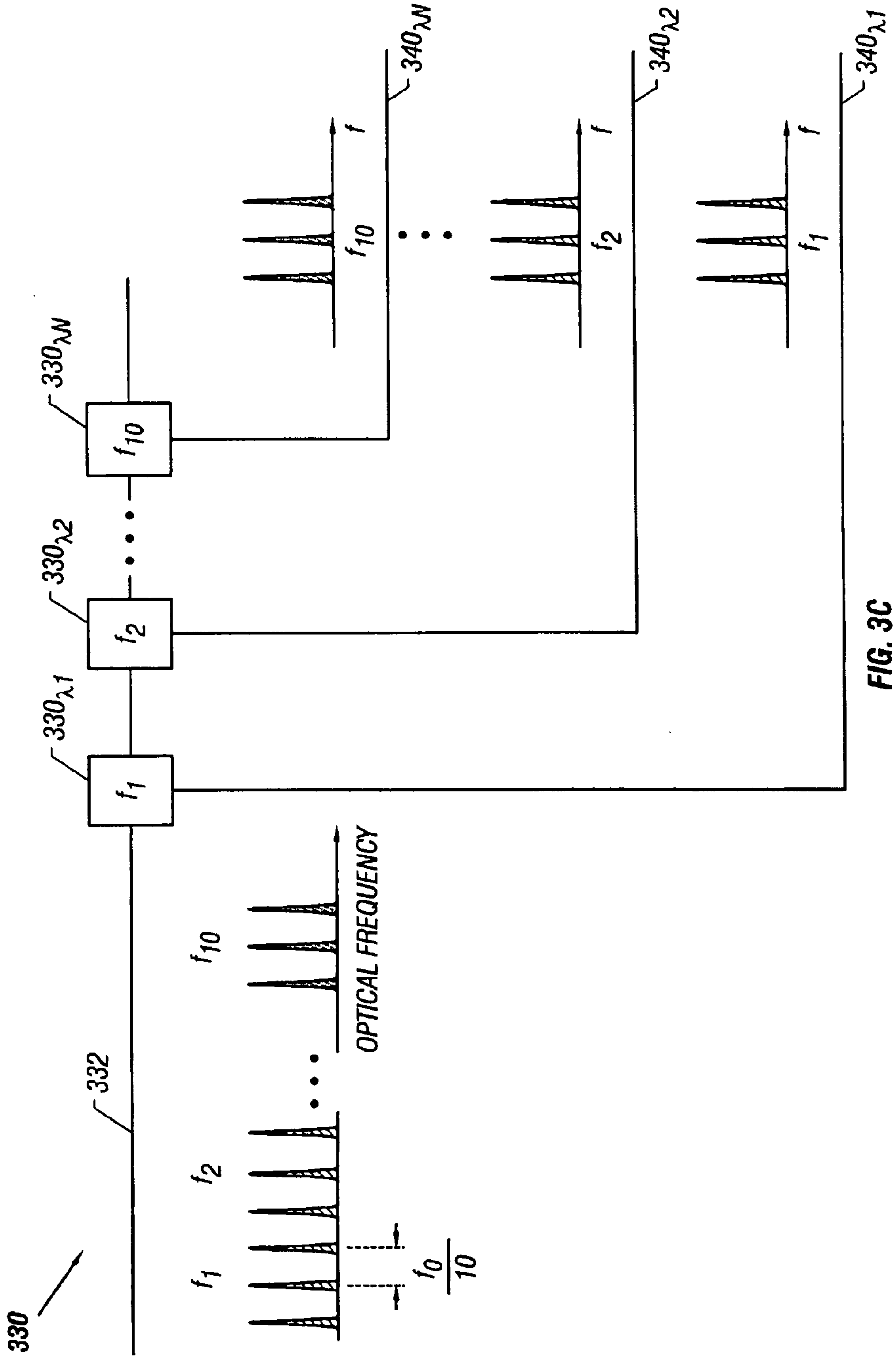

330
332
f_1
f_2
f_{10}
$\frac{f_0}{10}$
OPTICAL FREQUENCY
$330_{\lambda 1}$
$330_{\lambda 2}$
$330_{\lambda N}$
$340_{\lambda 1}$
$340_{\lambda 2}$
$340_{\lambda N}$
f

FIG. 3C

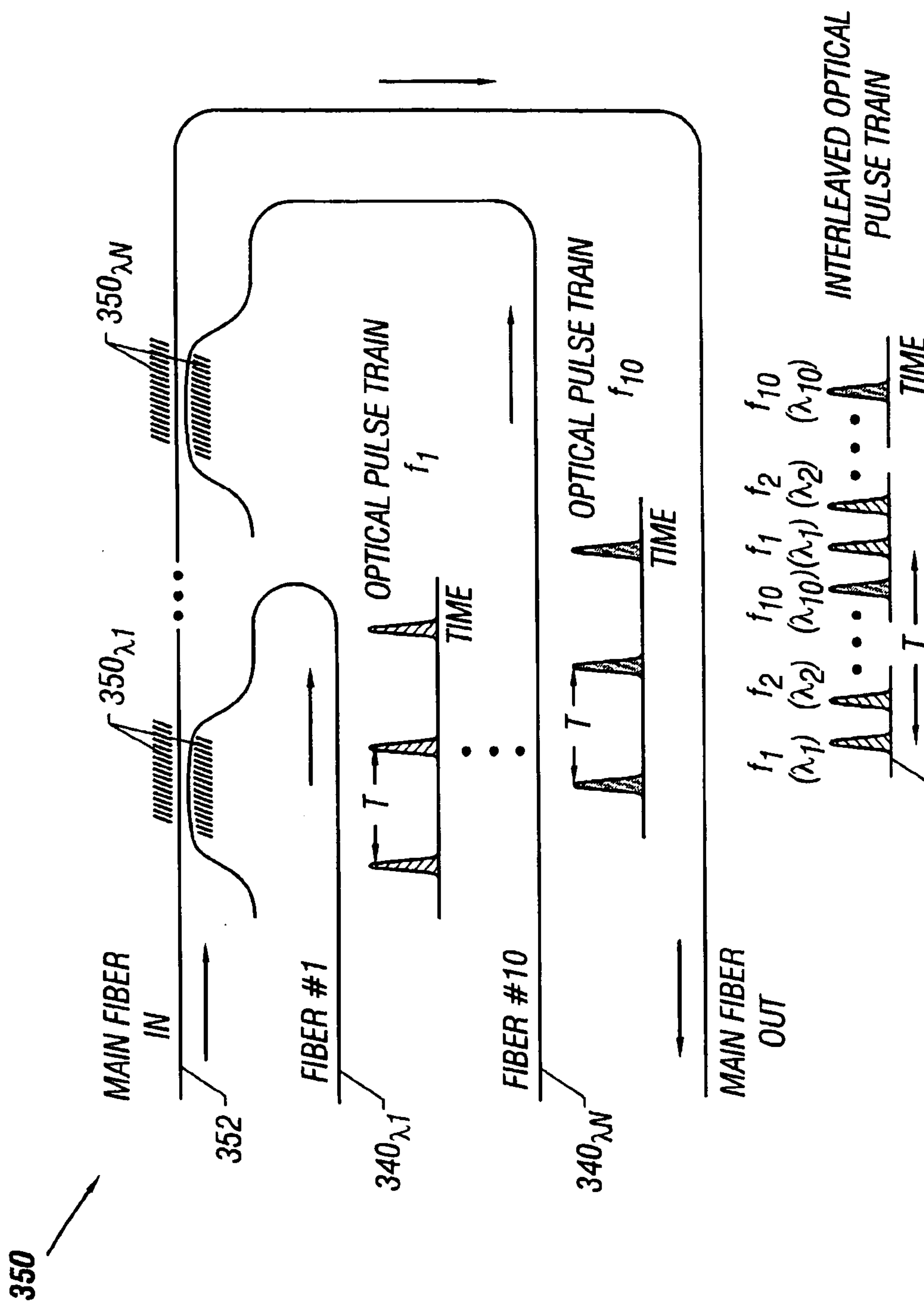

350
MAIN FIBER IN
352
FIBER #1
$340_{\lambda 1}$
FIBER #10
$340_{\lambda N}$
MAIN FIBER OUT
$350_{\lambda 1}$
$350_{\lambda N}$
OPTICAL PULSE TRAIN f_1
T
TIME
OPTICAL PULSE TRAIN f_{10}
T
TIME
INTERLEAVED OPTICAL PULSE TRAIN
f_1 (λ_1) f_2 (λ_2) f_{10} (λ_{10}) f_1 (λ_1) f_2 (λ_2) f_{10} (λ_{10})
T
TIME
212

FIG. 3D

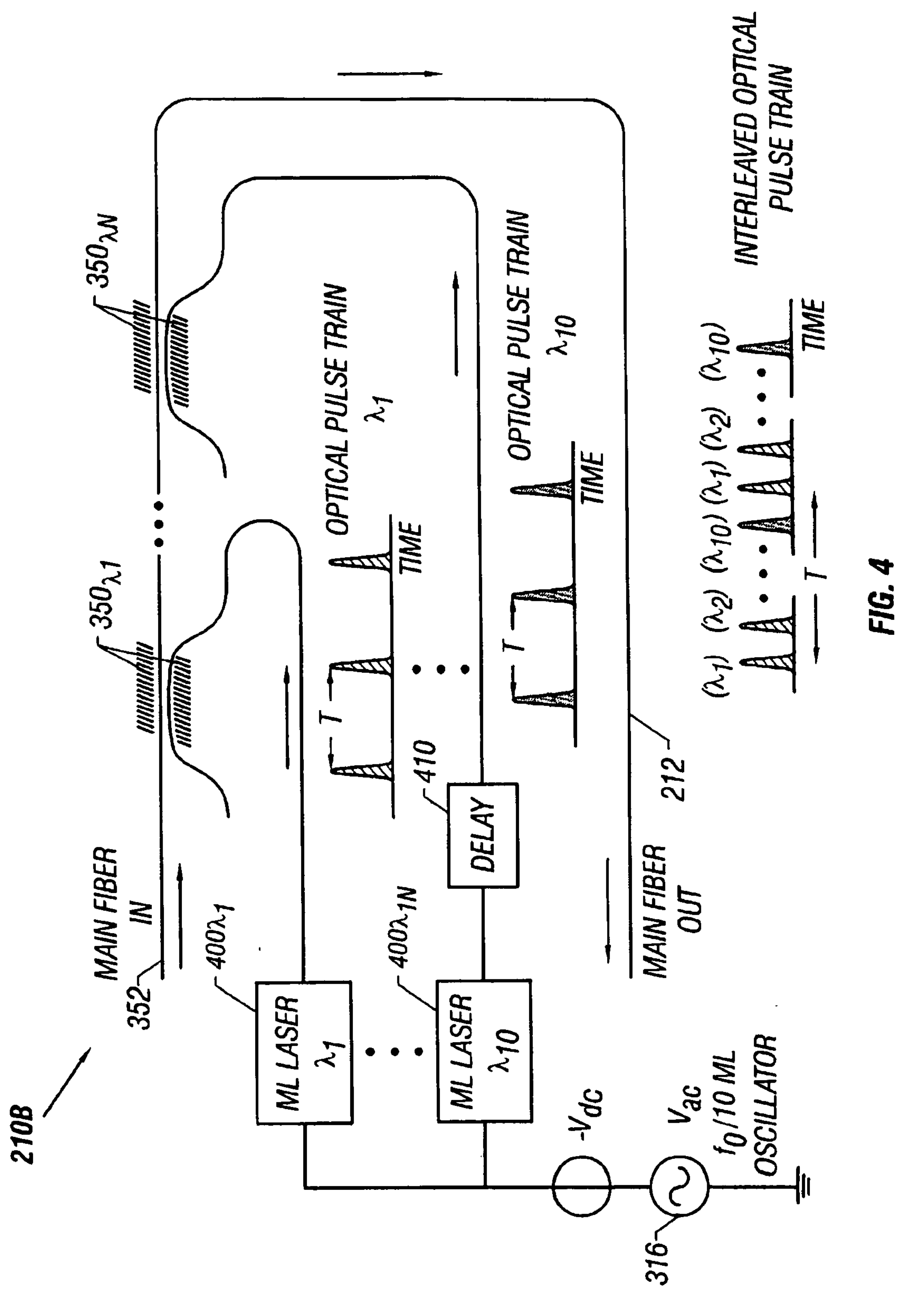

210B
352
MAIN FIBER IN
400λ1
ML LASER λ1
400λ1N
ML LASER λ10
-Vdc
Vac
f0/10 ML OSCILLATOR
316
DELAY
410
350λ1
350λN
OPTICAL PULSE TRAIN λ1
OPTICAL PULSE TRAIN λ10
T
TIME
212
MAIN FIBER OUT
INTERLEAVED OPTICAL PULSE TRAIN
(λ1) (λ2) (λ10) (λ1) (λ2) (λ10)
T
TIME

FIG. 4

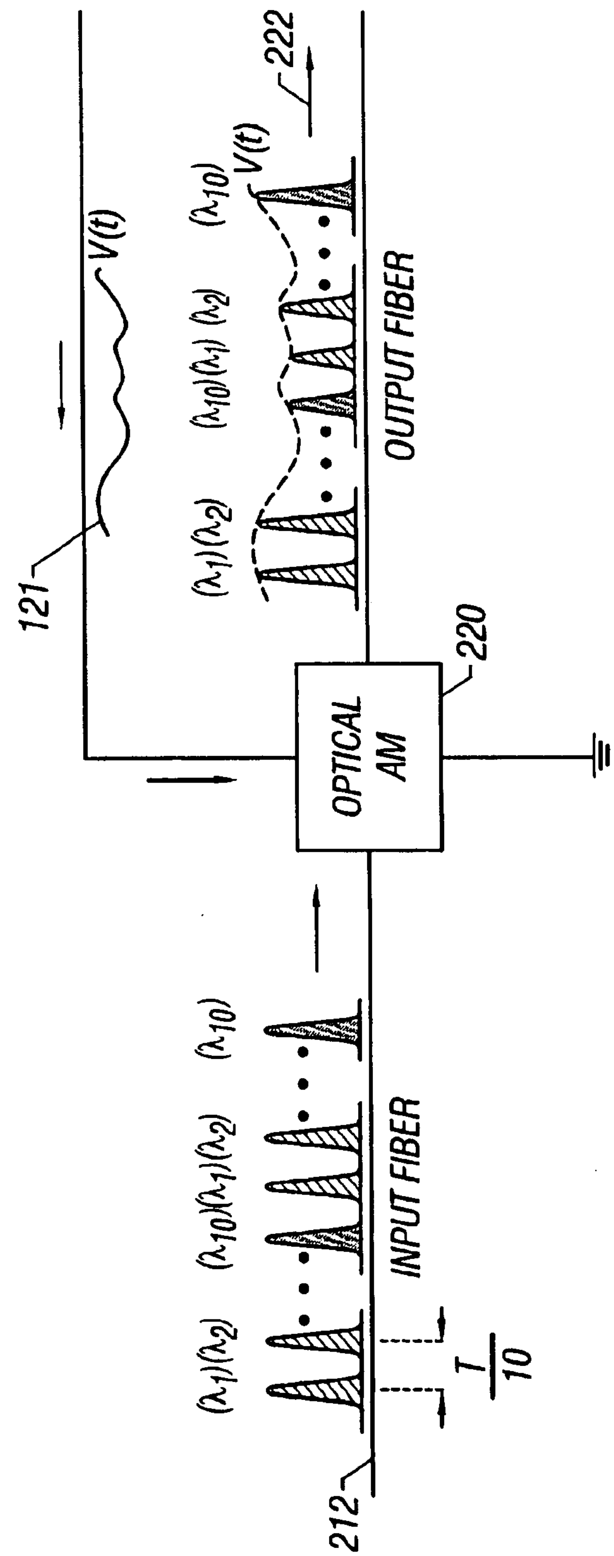

OPTICAL
AM
220
121
V(t)
222
V(t)
OUTPUT FIBER
INPUT FIBER
212
T
10
(λ_1)(λ_2)
(λ_{10})(λ_1)(λ_2)
(λ_{10})

FIG. 5

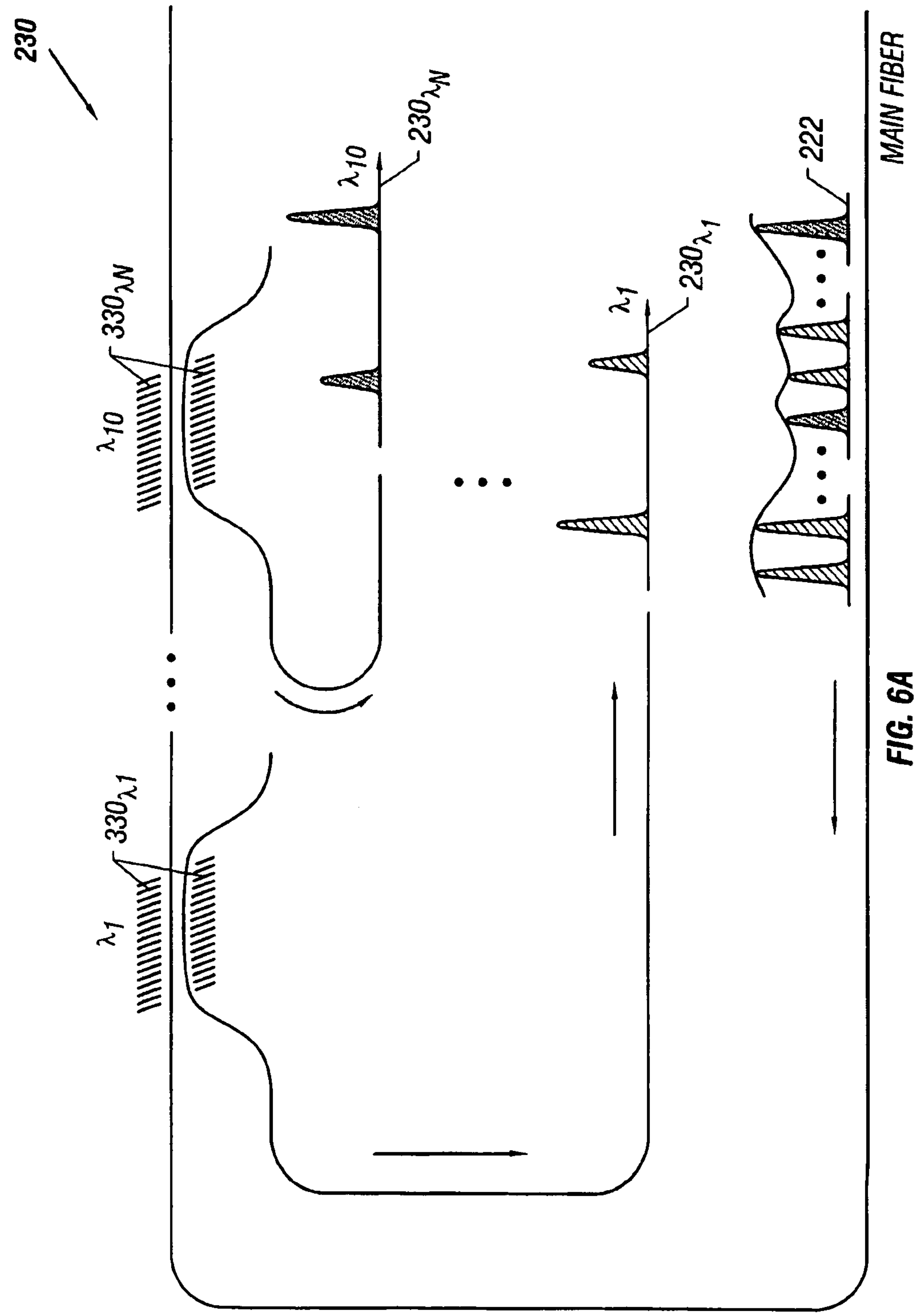
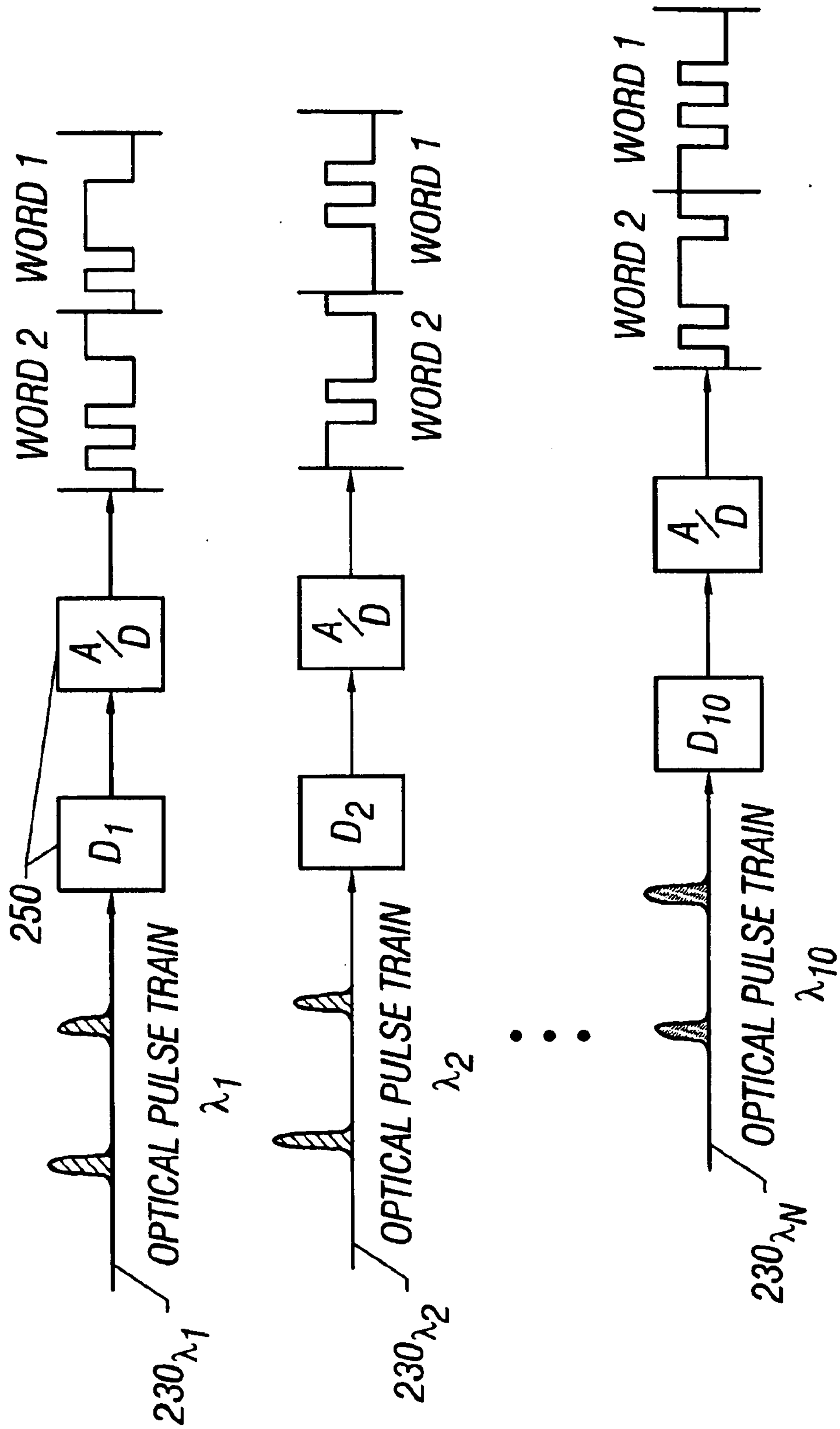

230
$330_{\lambda N}$
λ_{10}
$330_{\lambda 1}$
λ_1
λ_{10}
$230_{\lambda N}$
λ_1
$230_{\lambda 1}$
222
MAIN FIBER

FIG. 6A



WORD 2
WORD 1
WORD 2
WORD 1
WORD 2
WORD 1
A/D
A/D
A/D
D_1
D_2
D_{10}
250
OPTICAL PULSE TRAIN
λ_1
OPTICAL PULSE TRAIN
λ_2
OPTICAL PULSE TRAIN
λ_{10}
230_{λ_1}
230_{λ_2}
230_{λ_N}

FIG. 6B

SAMPLING AND PROCESSING SIGNALS BY USING OPTICAL PULSES

This application claims the benefit of U.S. Provisional Application No. 60/065,249, entitled "Time Interleaved Sampling by Optical Techniques and Its Application to Ultra High Speed A/D conversion" and filed on Nov. 18, 1997, which is incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates to sampling and processing of analog signals, more specifically, to analog-to-digital conversion using optical techniques.

BACKGROUND

Analog electronic signals can be represented or reconstructed by a certain set of discrete sampled values or samples. Many electronic applications use samples of analog signals instead of the analog signals. For example, digital data processing and communication systems use digital data converted from samples of an analog signal to achieve improved noise immunity and processing flexibility in data processing and transmission. Conversion of analog signals to digital data can be accomplished by first sampling the analog signals into sampled values and then digitizing the sampled values in a desired form.

A sampling rate or sampling frequency describes the number of samples taken from an analog signal per unit time (e.g., one second). The minimum sampling rate should be equal to or greater than the Nyquist rate, which is double the highest frequency in an analog signal, in order to preserve the minimum information content in the original analog signal. Thus, a high sampling rate is desirable in converting an analog signal with signal components at high frequencies into digital form. In addition, an analog signal may be oversampled at a sampling rate much higher than the Nyquist rate to improve the signal-to-noise ratio and/or precision of a subsequent analog-to-digital conversion.

Sampling of analog electronic signals is usually accomplished electronically by using electronic circuits. Electronic sampling techniques and circuits are well developed. The maximum sampling rate achievable by an electronic circuit is generally limited by the response times of the electronic components and the circuit configuration. This further limits the conversion speeds of many electronic analog-to-digital converters.

Such speed limitation in electronic digital-to-analog conversion can be an obstacle to many applications that require high-speed analog-to-digital conversion. Real-time digital video in applications such as telecommunication and machine vision is one such example. The performance of the real-time digital video in the existing video delivery on the Internet and in video conferencing systems is not only limited by the bandwidth limitation in the data transmission channels but also limited by the analog-to-digital conversion rates.

SUMMARY

Therefore, there exists a need for devices and techniques that provide high-speed sampling and analog-to-digital conversion.

The present disclosure define devices and techniques for sampling analog signals at high sampling rates by using optical pulses in a special way. It further provides devices and techniques for converting such high-rate samples into digital data.

One aspect of the disclosure describes generation of a train of dense pulses comprising a sequence of pulses that have different pulse signatures so that one pulse is distinguishable from adjacent pulses and different pulses with a common pulse signature can be separated from other pulses to form a new pulse train. The pulses are "dense" in a sense that the pulse repetition rate is higher than the upper switching rate of many electronic devices.

One example of such dense pulse trains may include a sequence of pulses that are centered at different wavelengths. One device for generating this pulse train includes a mode-locked laser for producing optical pulses with a known pulse repetition period, a plurality of optical demultiplexer (e.g., "drop" filters) connected in series and each configured to separate adjacent oscillation modes in each pulse near a different center wavelength and to transmit remaining modes in each pulse such that each demultiplexer produces a train of pulses of the same pulse repetition period at a different center wavelength, and a plurality of optical multiplexers (e.g., "add" filters) connected in series to form an optical path and configured to respectively couple the plurality of pulse trains at different center wavelengths to the optical path with a delay relative to one another so as to form an interleaved dense pulse train. This interleaved dense pulse train has a shortened pulse repetition period and a sequence of pulses at different center wavelengths within one pulse repetition period of the mode-locked laser.

Another device for generating the above interleaved dense pulse train comprises a plurality of mode-locked lasers respectively producing optical pulses at different center wavelengths with the same pulse repetition period, and a plurality of optical multiplexers (e.g., "add" filters) connected in series to form an optical path and configured to respectively couple the plurality of pulse trains from the mode-locked lasers to the optical path to form the interleaved pulse train.

A second aspect of the disclosure includes sampling an analog signal by using the above train of dense pulses. An optical modulate is used to modulate a property of the pulses in the interleaved dense pulse train in response to an analog signal and therefore impose the information in the analog signal onto the optical pulses. The analog signal may be in various forms such as an electrical analog signal that drives the optical modulator or an optical analog signal that interacts with the optical pulses to produce the modulation (e.g., a wave-mixing device). The property of the pulses may be the amplitude, phase, polarization, or other parameters of the optical pulses. One simple implementation is amplitude modulation by using an optical amplitude modulator that is driven by an analog electrical signal. This converts the information in the analog signal into amplitude variation of the dense pulses at a sampling rate equal to the repetition rate of the dense pulses.

A third aspect of the disclosure involves separating the information-bearing dense pulse train into a plurality of pulse trains according to their pulse signatures. In the above wavelength interleaved pulse train, pulses at different center wavelengths are separated into different pulse trains each with the same center pulse wavelength. Each pulse train has less pulses per unit time than the original pulse train. Hence, the pulse repetition rate is reduced to the low pulse repetition rate of the original unmodulated pulse trains. One or more optical demultiplexers, such as a set of optical "drop" filters respectively corresponding to the different center wavelengths, may be connected in series in the optical path of the dense pulse train to perform the pulse separation and to generate a plurality of parallel signal channels at different

center wavelengths and different time delays. Each signal channel may further include a photosensor for converting the modulated optical pulses into analog electrical pulses, and an electronic analog-to-digital converter for converting the analog pulses into digital data. The reduced pulse repetition rate of the pulse trains in the signal channels can be set to accommodate for the processing speed of the electronic analog-to-digital converters. The analog-to-digital conversion of all signal channels is performed electronically in parallel. The combined digital data from all signal channels includes all the information content of the analog signal if the repetition rate of the dense pulse train is equal to or greater than the Nyquist rate of the analog signal and hence can be used for subsequent digital signal processing.

One advantage of the systems in the disclosure is their unique optical sampling by dense pulses to achieve desired high sampling rates. A train of dense pulses comprising a sequence of a plurality of pulses at different center wavelengths can be formed to have a high pulse repetition frequency that is in general difficult, if not possible to achieve with electronic sampling devices. An increase in the sampling rate by a factor up to and or greater than 10^2 may be achieved.

Another advantage is an increased speed in analog-to-digital conversion. This is at least in part due to the optical processing in sampling and separating the modulated dense pulse train into multiple pulse trains at different center wavelengths and in part due to the parallel analog-to-digital conversion in the multiple signal channels.

These and other aspects and advantages will become more apparent in light of the accompanying drawings, the detailed description, and the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagram of a signal sampling device based on optical pulses with a high repetition rate.

FIG. 2 shows one implementation of the device of FIG. 1.

FIGS. 3A, 3B, 3C, and 3D show one embodiment of a pulse generator used in the device of FIG. 2.

FIG. 4 shows an alternative embodiment of a pulse generator used in the device of FIG. 2.

FIG. 5 illustrates amplitude modulation on optical pulses to sample an analog signal based on operation of an optical modulator.

FIG. 6A shows one embodiment of a drop filter module for separating time-wavelength interleaved pulses.

FIG. 6B illustrates operation of the analog-to-digital conversion by parallel electronic channels.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Signal sampling is conventionally achieved by using electronic pulses that are usually effected by switches or modulations. The repetition rate of the electronic pulses is the sampling rate.

An optical pulse train is not subject to many of the physical barriers that limit electrical signals, e.g., line capacitance and resistance. Hence, an optical signal in general can have a repetition rate much higher than what is possible for an electronic pulse train and can have sharp pulse edges. An optical pulse train can be modulated by using an analog signal, which may be electrical, optical or of other forms, to drive an optical modulator. The modulated pulses then become samples of the analog signal in the optical domain. A higher sampling rate, which may not be possible by electronic sampling techniques, can therefor be achieved.

However, such optical samples may not be easily converted into electronic pulses for further electronic processing since the repetition rate of the optical pulses can be too high for electronic circuits to respond or detect.

This difficulty can be overcome by using a plurality of parallel electronic channels to process the data contained in an optical pulse train. Each electronic channel is designated to process only a fraction of the data carried in the optical pulse train. An opto-electronic signal processing device can be implemented to combine the above high-speed optical sampling and parallel electronic processing to achieve sampling rates and processing speeds higher than the state of art electronic circuits.

FIG. 1 shows an embodiment of an opto-electronic device **100** that is based on the high-speed optical sampling and parallel electronic processing. An analog electronic signal **121** is to be sampled and may be converted into digital form. An optical pulse generator **110** produces an optical pulse train **112** with a high repetition rate, f_s. An optical modulator **120**, e.g., an electro-optical modulator, responds to the analog electronic signal **121** to modulate the optical pulses in the optical train **112** and hence produces a modulated optical train **122**. A property of an optical pulse, e.g., phase or amplitude, is modulated to encode the information of the analog signal **121** onto the optical pulse to represent a sample of the analog signal **121**.

An optical pulse separation module **130** separates the modulated optical pulse train **122** into a plurality of pulse trains $132P_1$, $132P_2$, . . . $132P_N$ (e.g., N number of pulse trains) each having a common reduced repetition rate of f_s/N. A series of N sequential pulses (indicated by P_1, P_2, . . . , and P_N) in the modulated optical pulse train **122** are separated to the pulse trains $132P_1$, $132P_2$ . . . $132P_N$, respectively. Hence, the first pulse train $132P_1$ has pulses P_1, P_{1+2N}, and so on; the second pulse train $132P_2$ has pulses P_2, P_{2+N}, P_{2+2N}, and so on; and the last pulse train $132P_N$ has pulses P_N, P_{2N}, P_{3N}, and so on. The separated pulse trains $132P_1$, $132P_2$, . . . , $132P_N$ are then routed to N parallel optical detectors **140** (D_1, D_2, . . . , and D_N) and are converted into N parallel electronic channels **142**.

One way to implement above pulse separation is generate the dense pulse train **112** with different pulse signatures, e.g., pulse wavelength or pulse polarization. Each pulse in a sequence of pulses is assigned a pulse signature different from adjacent pulses or any other pulses in the sequence. The pulse separation module **130** separates these pulses according to the signatures to produce different pulse trains as the parallel optical channels.

Since each separated optical pulse train has a reduced repetition rate of f_s/N, each parallel electronic channel **140** can operate at this reduced rate $f_{electronic}=f_s/N$ rather than the high rate f_s. Each electronic channel may include an analog-to-digital converter ("ADC") so that the analog information in the modulated optical pulse train **122** is converted into digital form by N parallel ADCs. For given $f_{electronic}$ and f_s, the number N may be adjusted to match the total processing rate of parallel electronic channels and the optical sampling rate of the optical pulse train **122**: $f_{electronic}=f_s/N$. An improvement of the processing speed by a factor of N can therefore be achieved over the state-of-art electronic devices.

For many practical applications, N may be chosen between 10 and 100. Hence, for $f_{electronic}$=10 GHZ and

N=10, a sampling rate of f_s=100 GHZ can be achieved by using the system **100**.

FIG. **2** shows one implementation **200** of the system **100** in FIG. 1. Certain aspects of this system is disclosed by Yariv and Koumans in "Time interleaved optical sampling for ultra-high speed A/D conversion," Electronic Letters, vol. 34 (21) pp.2012–2013 (1998), which is incorporated herein by reference. An optical pulse generator **210** is configured to produce an optical pulse train **212** with sequentially repetitive sets of pulses where each set includes N sequential pulses centered at different wavelengths $\lambda_1, \lambda_2, \ldots, \lambda_N$ at a repetition rate f_s. An optical amplitude modulator **220** modulates the amplitudes of the pulses in the pulse train **212** to produce an amplitude-modulated pulse train **222**. Hence, the amplitude variation in the pulse train **222** represents the information in the analog signal **121**.

The optical pulse separation module **130** in the FIG. **1** is implemented by using an optical filter module **230** to separate the pulses in the pulse train **222** according to their wavelengths into N different pulse trains **230**λ_1, **230**λ_2, **230**λ_3, . . . , and **230**λ_N. Each pulse train **230**λ_i (i=1, 2, . . . N) has pulses only of the wavelength λ_i and at a reduced common repetition rate of f_s/N. N parallel electronic channels, each including an optical detector **240** and an ADC, converts the analog samples in the N different pulse trains **230**λ_1, **230**λ_2, **230**λ_3, . . . , and **230**λ_N into digital data.

The optical pulse generator **210** may be formed of a mode-locked laser **310**, a set of demultiplexers **330** such as "drop" filters connected in series, and a set of optical multiplexers **350** such as "add" filters connected in series as shown in FIG. 3A. Many optical add and drop filters may be used. See, for example, Kewitsch et al., "All-fiber zero-insertion-loss add-drop filter for wavelength-division multiplexing," Optics Letters, Vol.23(2), pp. 106–108 (1998) and Agrawal, "Fiber-optic communication systems", 2nd edition, Chapter 7, John Wiley & Sons, New York (1997), which are incorporated herein by reference.

The mode-locked layer **310** is preferably actively mode-locked by using an external electronic oscillator at an oscillation frequency $f_{osc}=f_s/N$. Both f_{osc} and N may be adjusted so as to achieve a desired f_s. One example of the mode-locked laser is shown in FIG. 3B where an edge-emitting semiconductor laser **312** is driven by a current source **314** and is mode-locked by a mode-locking oscillator **316**. Other mode-locked lasers may also be used, including other types of semiconductor lasers and fiber lasers.

The laser output from the laser **310** is a pulse train **320** with a repetition rate of f_s/N. Each pulse includes spectral components of different wavelengths emitted by the laser medium. Hence, the pulse train **320** can be filtered to produce one or more optical trains centered at desired wavelengths selected from the spectral components in the laser output. The drop filters **330** are specifically designed to achieve this filtering.

Referring to FIG. 3C, N drop filters **330**λ_1, **230**λ_2, . . . , and 330λ_N at different wavelengths $\lambda_1, \lambda_2, \ldots$, and λ_N are connected in series in a fiber **332** to form an optical path that receives the optical pulse train **320** from the laser **310**. Each drop filter is configured to select a spectral component at a wavelength λ_i (i=1, 2, . . . , N) to produce an output and transmits the remaining spectral components down the fiber **332**. Hence, the selected output **340**λ_i from a drop filter **330**λ_i is a pulse train centered at the wavelength λ_i and has the same pulse repetition rate f_s/N as the unfiltered pulse train **320**. Since the spectral components at wavelengths other than λ_i are eliminated, the pulse width of the selected output **340**λ_i is broadened compared to the pulse width of the unfiltered pulse train **320**.

The add filters **350** are designed to interleave pulse trains **330**λ_1, **330**λ_2, . . . , and **330**λ_N to form a dense pulse train **212** with a repetition rate of f_s. One implementation is illustrated in FIG. 3D. N add filters **350**λ_1, **350**λ_2, . . . , and **350**λ_N are connected in series in a fiber **352**. Each add filter **350**λ_i (i=1, 2, . . . , N) is connected to receive a respective output **340**λ_i from the drop filter **330**λ_i and add the output **340**λ_i to the fiber **352**. A constant temporal delay is introduced (by using an fiber delay line or other optical delay element) to each add filter **350**λ_i so that the outputs **340**λ_1, **340**λ_2, . . . , and **340**λ_N are sequentially added to the fiber **352** and the temporal separation between the first output **340**λ_1 and the last output **340**λ_N is equal to the pulse separation produced by the laser **310**.

Thus, the newly generated pulse **212** in the fiber **252** is a special pulse train of a repetitive pulse sequence which is sequentially formed of N pulses of different wavelengths. In every period of $1/f_s$, a pulse at a different wavelength arrives. In a period of $T=(N-1)/Nf_s$, the spectral pattern of the pulses repeats, i.e., the wavelength of a pulse repeats after every N pulses. This pulse train has the unique property that the wavelength of each pulse in the train is different from those of its neighbors in a controlled fashion. The pulses are essentially identical in shape and equally spaced in time.

FIG. **4** shows another alternative implementation **210B** of the pulse generator **210** in FIG. **2**. N different mode-locked lasers **400**λ_1, **400**λ_2, . . . , and **400**λ_N are used to generate N pulse trains of the same repetition rate at f_s/N but at different wavelengths $\lambda_1, \lambda_2, \ldots$, and λ_N. The mode-locked lasers **400**λ_1, **400**λ_2, . . . , and **400**λ_N are mode-locked by a common mode-locking oscillator **316**. The outputs of the lasers are then interleaved in a fiber **352** to form the dense pulse train. The output of each laser is properly delayed by using a delay element **410**. The multilayers can be integrated monolithically to be compact and the delay between pulses of different wavelengths may also be electronically controlled by phase delays of RF drivers to the individual lasers.

The optical amplitude modulator **220** in FIG. **2** modulates the amplitude of each pulse in the dense time-wavelength interleaved pulse train **212** to obtain samples of an analog signal **121** v(t) (e.g., a rf signal). The sampling frequency is f_s, the pulse repetition rate. The analog signal **121** is applied as a voltage (or current) to the modulator **220** such that the instantaneous transmitted optical intensity is proportional to v(t) or some representation of v(t). This is illustrated in FIG. **5**.

Since each pulse undergoes a multiplication by the optical modulator **220** by a factor kv(t) where k is a constant of the modulator **220**. The result is a sampling of the signal by the optical pulses. The variation of v(t) during the passage of an individual pulse is assumed to be negligible.

The modulated pulse train **222** from the modulator **220** has a repetition rate f_s which may be fast for conventional electronics to process. One aspect of the invention is to separate the pulse train **222** into N pulse trains of a reduced pulse rate so that N optical detectors **240** can be used to convert the pulses into N parallel electronic channels and therefore to process the data in parallel.

FIG. 6A shows one embodiment of the drop filter module **230** for separating the dense pulse train **222**. The construction is similar to the device shown in FIG. 3C used in the pulse generator shown in FIG. 3A. The modulated pulses centered at a common wavelength λ_i (i=1, 2, . . . , N) are selected out by a drop filter at that wavelength λ_i to form a

new modulated pulse train **230**λ_i with a reduced pulse repetition rate at f_s/N, since the spectral pattern of the pulses repeats every N pulses in the pulse train **222**. N modulated pulse trains are generated among which the information of the analog signal **121** are distributed. The pulse trains are further converted into N electronic channels of digital data as shown by FIG. 6B.

Although the present invention has been described in detail with reference to the preferred embodiments, various modifications and variations may be possible without departing from the spirit of the invention. For example, pulse trains with different wavelengths can also be generated in other ways using a single laser, for example, by spectral slicing. See, Knuss et al., "Scalable 32 channel chirped-pulse WDM source," Electronic Letters, vol.32(14), pp.1311–1312 (1996). Other mode-locked lasers can also be used to generate the dense pulse trains such as lasers disclosed by Sanders et al. in "Timing jitter and pulse energy fluctuations in a passively mode-locked 2-section quantum-well laser coupled to an external cavity," Applied Physics Letters, Vol.59(11), pp.1275–1277 (1991), by Arahira et al. "Transform-limited optical short-pulse generation at high repetition rate over 40 GHz from a monolithic passively mode-locked DBR laser diode," IEEE Photonics Technology Letters, Vol.5(12), pp.1362–1365 (1993), and by Salvatore et al. "Wavelength tunable source of subpicosecond pulses from CW passively mode-locked 2-section multiple-quantum-well laser," IEEE Photonic Technology Letters, vol.5(7), pp.756–758(1993). Each disclosure of the above references is incorporated herein by reference.

These and other variations and modifications are intended to be encompassed by the appended claims.

What is claimed is:

1. A signal processing device, comprising:

an optical pulse generator operable to produce a sampling optical pulse train of optical pulses at a sampling pulse repetition rate; and

an optical modulator disposed to receive said sampling optical pulse train and configured to perform a modulation on a selected property of said optical pulses in said sampling optical pulse train to produce a modulated optical pulse train at said sampling repetition pulse rate in response to an analog signal,

wherein said modulated pulses are samples indicative of information in said analog signal.

2. The device as in claim **1**, wherein said optical modulator includes a phase modulator or an amplitude modulator.

3. The device as in claim **1**, wherein said optical modulator includes an electro-optical modulator.

4. The device as in claim **1**, wherein said optical pulse generator includes at least one mode-locked laser that locks laser modes according to an oscillator.

5. The device as in claim **4**, wherein said optical pulse generator further includes at least one add filter.

6. The device as in claim **4**, wherein said optical pulse generator further includes at least one drop filter.

7. The device as in claim **4**, wherein said optical pulse generator further includes:

a plurality of wavelength drop filters connected relative to one another in series to filter said optical pulses from said laser to produce a plurality of pulse trains centered at different wavelengths; and

a plurality of wavelength add filters coupled relative to one another in series to respectively receive said pulse trains from said wavelength drop filters, said add filters operable to interleave pulses of different wavelengths from said pulse trains to produce said sampling optical pulse train.

8. The device as in claim **1**, wherein said optical pulse generator is so configured that said sampling pulse train includes a repetitive sequence of optical pulses that are centered at different wavelengths from one another.

9. The device as in claim **1**, further comprising a pulse separation module disposed to receive said modulated pulse train from said optical modulator and configured to separate said modulated pulse train into N pulse trains where N is an integer greater than 1, wherein each of said N pulse trains has a repetition pulse rate less than said sampling repetition pulse rate by a factor of N and is centered at a different wavelength.

10. The device as in claim **9**, wherein said pulse separation module further includes at least one drop filter.

11. The device as in claim **10**, wherein each electronic channel includes an analog-to-digital converter.

12. The device as in claim **10**, further comprising a plurality of analog-to-digital converters each connected to one of said analog-to-digital converters.

13. The device as in claim **9**, further comprising N electronic channels connected in parallel with respect to one another, wherein each electronic channel is connected to receive one of said N pulse trains from said pulse separation module and to electrical signals.

14. The device as in claim **1**, wherein said modulated optical pulse train includes a repetitive sequence of optical pulses in which each optical pulse has a wavelength different from wavelengths of adjacent optical pulses, and further comprising:

a pulse separation module to process said modulated optical pulse train to produce a plurality of optical pulse trains centered at different wavelengths and at a pulse repetition rate less than said sampling pulse repetition rate; and

a plurality of optical detectors to respectively receive and convert said optical pulse trains into a plurality of channels of electronic pulses.

15. The device as in claim **14**, further comprising a plurality of analog-to-digital converters respectively coupled to said plurality of optical detectors to convert said plurality of channels of electronic pulses into digital form.

16. The device as in claim **14**, wherein said analog signal includes a radio-frequency signal.

17. The device as in claim **14**, wherein said pulse separation module includes a plurality of wavelength drop filters connected in series relative to one another and each drop filter is operable to select out pulses at a selected wavelength in said modulated sampling optical pulse train to produce one of said optical pulse trains and transmit optical pulses at other wavelengths.

18. A signal processing device, comprising:

an optical pulse generator operable to produce a sampling optical pulse train of optical pulses at a sampling pulse repetition pulse rate, wherein a wavelength of each optical pulse is different from wavelengths of adjacent optical pulses;

an optical modulator disposed to receive said sampling optical pulse train and configured to perform a modulation on a selected property of said optical pulses in said sampling optical pulse train to produce a modulated optical pulse train at said sampling repetition pulse rate in response to an analog signal, wherein said modulated pulses represent samples of said analog signal;

a pulse separation module having a plurality of drop filters connected in series to produce a plurality of parallel

pulse trains centered at different wavelengths and at a pulse repetition rate smaller than said sampling pulse repetition rate, each drop filter selecting one spectral component in each optical pulse of said modulated sampling optical pulse train to produce one of said parallel pulse trains and transmitting remaining spectral components; and

a plurality of optical detectors to respectively receive said parallel pulse trains and convert said pulses into a plurality of channels of electronic pulses.

19. The device as in claim **18**, wherein said pulse generator includes:

a mode-locked laser producing optical pulses in response to an external oscillator that oscillates at a frequency less than said sampling pulse repetition rate;

a plurality of drop filters connected relative to one another in series to filter said optical pulses from said laser to produce a plurality of pulse trains centered at different wavelengths; and

a plurality of add filters connected relative to one another in series to respectively receive said pulse trains from said drop filters, said add filters operable to interleave pulses of different wavelengths from said pulse trains to produce said sampling optical pulse train.

20. The device as in claim **19**, further including an optical fiber to couple said drop filters in series.

21. The device as in claim **19**, further including an optical fiber to couple said add filters in series.

22. The device as in claim **18**, wherein said pulse generator includes:

a plurality of mode-locked lasers operating to produce pulse trains at different wavelengths based a mode-lock operation according to a common oscillator at said sampling pulse repetition rate; and

a plurality of add filters connected relative to one another in series to respectively receive said pulse trains from said lasers, said add filters operable to interleave pulses of different wavelengths from said pulse trains to produce said sampling optical pulse train.

23. The device as in claim **18**, wherein said optical modulator includes a phase modulator or an amplitude modulator.

24. The device as in claim **18**, wherein said optical modulator includes an electro-optical modulator.

25. The device as in claim **18**, further including at least one optical fiber to transmit an optical pulse.

26. A method of sampling an analog signal, comprising:

producing a sampling optical pulse train of optical pulses at a sampling pulse repetition pulse rate, wherein a wavelength of each optical pulse is different from wavelengths of adjacent optical pulses; and

controlling an optical modulator by using the analog signal so as to modulate a selected property of said optical pulses in said sampling optical pulse train to produce a modulated optical pulse train at said sampling repetition pulse rate,

wherein said modulated pulses represent samples of said analog signal.

27. The method as in claim **26**, further comprising:

separating said modulated optical pulse train into a plurality of parallel pulse trains centered at different wavelengths and at a pulse repetition rate less than said sampling pulse repetition rate;

converting each parallel pulse train into electronic pulses; and

converting said electronic pulses into digital form.

28. The method as in claim **27**, wherein said optical modulator includes a phase modulator or an amplitude modulator.

29. A method for sampling an analog signal, comprising:

generating a sampling optical pulse train of optical pulses at a sampling pulse repetition rate and each having a wavelength different from wavelengths of adjacent optical pulses, said sampling optical pulse train including a repetitive sequence of optical pulses that are centered at different wavelengths from one another; and

modulating a selected property of said optical pulses in said sampling optical pulse train according to a signal variation in the analog signal to produce a modulated optical pulse train at said sampling pulse repetition rate so that optical pulses in said modulated optical pulse train are samples of the analog signal.

30. The method as in claim **29**, further comprising separating said modulated optical pulse train into a plurality of optical pulse trains centered at different wavelengths and at a pulse repetition rate less than said sampling pulse repetition rate.

31. The method as in claim **30**, further comprising:

converting each optical pulse train into a train of electronic pulses; and

converting said train of electronic pulses into digital form to represent information in the analog signal.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 6,219,172 B1
DATED : April 17, 2001
INVENTOR(S) : Amnon Yariv

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 1,
Line 63, delete "define" and insert -- includes --.

Column 3,
Line 57, before "switches", insert -- electronic --.
Line 58, delete "modulations" and insert -- modulators --.

Column 4,
Line 37, delete "to" and insert -- into --.
Line 45, after "is", insert -- to --.

Column 7,
Line 20, after "al.", insert -- in --.
Line 25, after "al.", insert -- in --.

Drawings,
Please replace FIG. 4 with the attached corrected figure.

Signed and Sealed this

Eighteenth Day of June, 2002

Attest:

JAMES E. ROGAN
Director of the United States Patent and Trademark Office

Attesting Officer

7/10

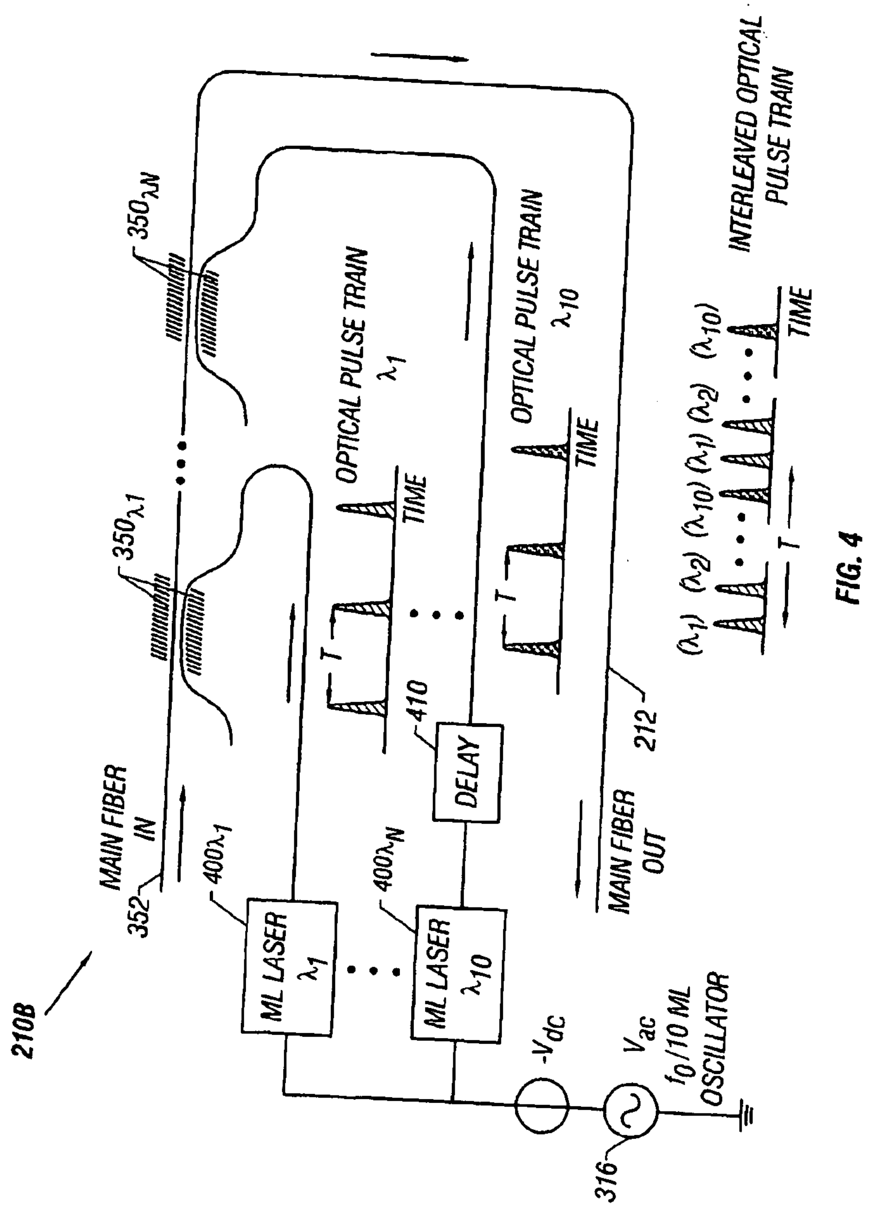

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FIG. 4